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Calculation of the Cost-Effectiveness of a PV Battery System

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Abstract

A possible way to calculate the cost-effectiveness of a photovoltaic system combined withelectric energy storage for a household is presented in this paper. To evaluatethe electricity costs, of the PV-battery system, the progression of the power demand and electricity production is evaluated and compared with cost and revenue of the resulting energy flow based on the electricity purchase prices and the EEG bonus for the feed in of renewable solar energy.The results show that solar applications with electricity storages can be profitable. But the high purchase price of the storage reduces the financial gain of the photovoltaic system. This paper also reveals that in the examined case redox flow batteries are the most promising technology and lead acid batteries are more lucrative than lithium ion batteries due to their lower initial costs. The calculation can predict the cost-effectiveness of a solar system with energy storage and therefore help to find the bestbattery sizefor a certain household.

Solar energy storage,cost-effectiveness, energy storage, electricity storage, house storage, photovoltaic storrage, profitability, PV battery, battery.

1. Introduction

Solar energy storages are becoming more and more popular in Germany. But providers of battery storage systems for photovoltaic applications often just give vague information about their profitability, which are hard to check. The reason is probably that it depends on a variety of criteria. At the moment it is certainly the independence and not the financial return, which is the main reason for the customers to install a storage system. But such a system should not become a bad deal. Therefore, a detailed evaluation of costs and values is strongly recommended.

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Nomenclature

a		year
A		albedo (-)
A_{gain}		profit (€)
A_{panels}		effective area of the solar panels (m²)
A_{PV}		costs for photovoltaic system (€)
$A_{storage}$		costs for storage system (€)
E_{-}		electricenergy consumptions with photovoltaic and storage system (kWh)
E_{+}		feed-in of electric energy (kWh)
E_{demand}		electric energy consumptions without PV-plant and battery (kWh)
EEG		German Renewable Energy Act
$G_{clearsky}$		global clear-sky irradiance (W/m²)
$G_{diffuse}$		diffuse irradiance (W/m²)
$G_{diffuse, r}$		diffuse irradiance on the roof (W/m²)
$G_{direct, r}$		direct irradiance on the roof (W/m²)
G_{global}		global irradiance (W/m²)
$G_{reflected, r}$		from the ground reflected irradiance on the roof (W/m²)
G_{total}		total irradiance on the roof (W/m²)
k_{aging}	= 0.008	coefficient describing the power loss due aging (1/year)
k_{EEG}	= 14.07	bonus for feed-in guaranteed in the German Renewable Energy Act (cent/kWh)
k_{tariff}		electricity tariff (cent/kWh)
$k_{Temp.}$	= 0.004	temperature-power coefficient (-)
P		power (W)
$P_{nominal}$		nominal power output (W)
P_{PV}		power output (W)
t		Time (s)
v		factor for period length (s)
Y		random number between 0 and 1
γ_r		pitch of the roof (°)
γ_S		solar altitude (°)
$\eta_{inverter}$		efficiency of the inverter (-)
η_{STC}		efficiency of the solar panels (-)
ϑ_{day}		daytime temperatures (°C)
ϑ_{panels}		temperature of the solar panels (°C)
Θ_r		incidence angle of the sun rays (°)

2. Calculation of the costs and profits

For the calculation, the chronological sequence of the photovoltaic applications' energy production is compared to the energy consumption of the home owner. In case of energy spillover, the battery is charged. In case the current power output of the photovoltaic system is not sufficient to power the household, the battery gets discharged. Subsequently, the grid is used to supply the house. If the battery is fully charged, the excess energy is fed into the grid. The assumption was made that the losses during battery charging and discharging are equal.Together, theyconstitutethe efficiency factor, shown in table 1. In conclusion,the electric power consumptions of every time interval can be added up in order to get the whole power consumption and the whole feed-in. The feed-in (E_{+}) can be converted into the financial gain by the EEG bonus (k_{EEG}) and the electricity consumptions (E_{demand}, E_{-})multiplied by the electricity tariff (k_{tariff})equate to the electricity costs. The financial gain (A_{gain}) is ascertained by comparing the system with a twenty yearlong purchase of electricity without any investments. In thecalculation time-steps of 15 minutes are used.

$$A_{gain} = E_{\text{demand}} \cdot k_{tariff} - \left(A_{PV} + A_{storage} + E_{-} \cdot k_{tariff} - E_{+} \cdot k_{EEG}\right) \tag{1}$$

The return is the ratio of gain to costs per twenty years.

$$i = \frac{A_{gain}}{\left(A_{PV} + A_{storage}\right)} \cdot \frac{1}{20} \tag{2}$$

All parameters of the calculation program are adjustable, soeven real storages can be quickly analyzed.

2.1. Generated electricity

The photovoltaic panels' output power is determined on the basis of irradiance data from the internet platform PVGIS (G_{global}, $G_{diffuse}$, $G_{clearsky}$, ϑ_{day}). Variation of the solar irradiance and therefore in energy income is taken into account by using the followingformula. The clear-sky global irradiance is the maximal possible momentary value for the weather-dependent irradiance. Average annual and monthly amounts of irradiance don't change due to this modification.

$$G_{weather} = G_{global} + \begin{pmatrix} for\ G_{clearsky} - G_{global} < G_{global}, G_{clearsky} - G_{global} \\ for\ G_{clearsky} - G_{global} > G_{global}, G_{global} \end{pmatrix} \cdot \sin\left(\frac{t}{v}\right) \cdot Y \begin{matrix} \text{min} = 0 \\ \text{max} = 1 \end{matrix} \tag{3}$$

The values for irradiance and temperature are converted in the total irradiance on the solar panels (G_{total})and their temperature (ϑ_{panels}).

$$G_{total} = G_{direct,\,r} + G_{diffuse,\,r} + G_{reflected,\,r} \tag{4}$$

$$G_{direct,\,r} = \left(G_{global} - G_{diffuse}\right) \cdot \frac{\cos(\Theta_r)}{\sin(\gamma_S)} \tag{5}$$

$$G_{diffuse,\,r} = 0.5 \cdot G_{global} \cdot \left[1 + \cos(\gamma_E)\right] \tag{6}$$

$$G_{reflected,\,r} = 0.5 \cdot G_{global} \cdot A \cdot \left[1 - \cos(\gamma_E)\right] \quad [1] \tag{7}$$

In the last step, the power output is calculated from the technical specification of the solar system and the data on irradiance and temperature. The power declension due to temperature and aging is also considered.

$$P_{PV} = G_{total} \cdot A_{panels} \cdot \eta_{STC} \cdot \eta_{inverter} \cdot \left[1 - k_{Temp.} \cdot \left(\vartheta_{panels} - 25°C\right)\right] \cdot k_{aging} \cdot a \tag{8}$$

$$\eta_{inverter} = 0.996 - \frac{0.008}{\frac{P}{P_{\text{nominal}}}} - 0.04 \cdot \frac{P}{P_{\text{nominal}}} \tag{9}$$

2.2. Electricity demand

The power demand is created by simulating the consumer behavior. The load curve represents the consumption of electric installations in the household when they are operated. The disadvantageous case for the self-consumption, whereupon the residents work on weekdays and cook in the evening, is studied. The load curve is based on a household, consisting of two persons and spending 3514 kWh each year.

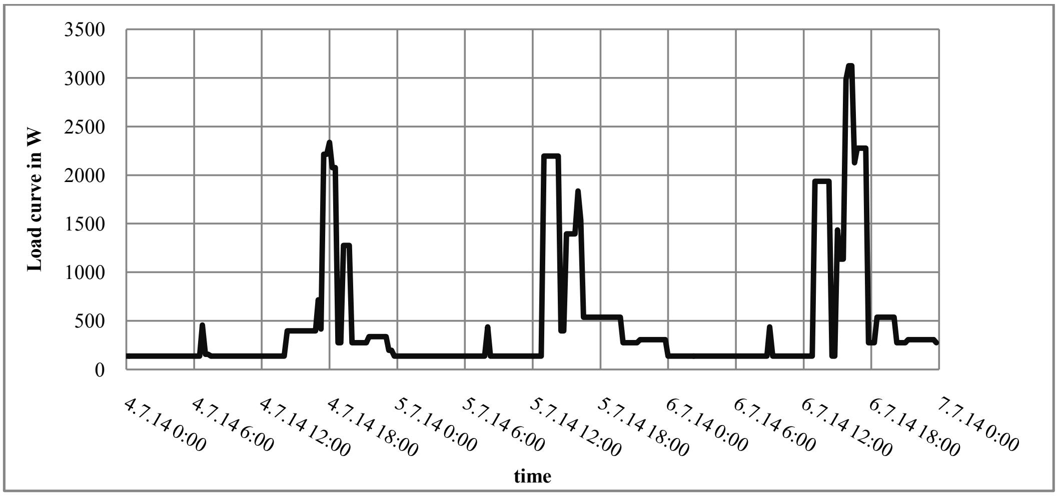

Fig. 1.Course oftheelectricity consumption on a weekday (8.4 kWh), Saturday (10.6 kWh) and Sunday (13.1 kWh).

2.3. Development of the electricity tariff

To calculate the electricity costs, a scenario for the electricity tariff's future development had to be created. Provider of battery storage systems often assume an increase in price by five or six percent per year. That seems to be a lot. So the prediction from GüntherOettinger, the European Commissioner for Energy, is also examined [2]. He claims that until 2030 the tariffs climb by 50 %, inflation-adjusted. Afterwards, the price should stabilize and start to decline (see figure2).

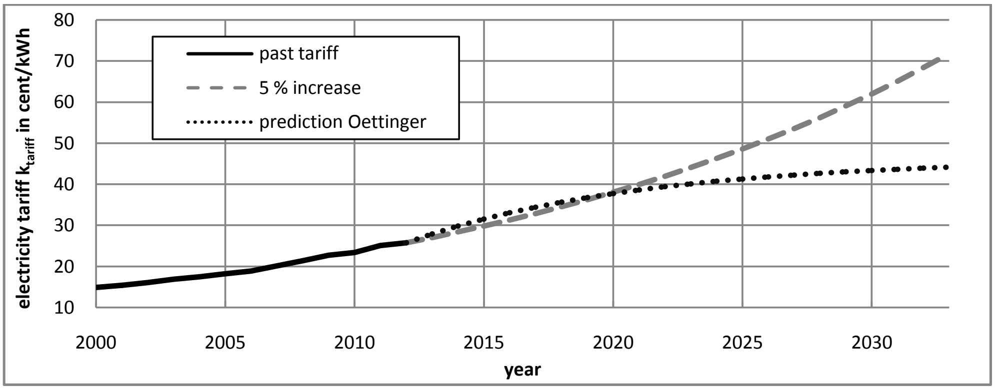

Fig. 2.Possible developments of the electricity tariff.

2.4. Costs of solar system

According to the BundesverbandSolarwirtschaft, the investment cost of a solar system (A_{PV}) is currently 1698 €/kWp (after tax). In addition, there are annual costs of 100 € for maintenance, another 80 € for insurance and a singular replacement of the inverter in the considered twenty years.For the inverter, the following cost equation was determined by an own market research: 183 €/kWp + 678€.

2.5. Costs of storage system

To determine the costs of a storage system, a market research was conducted. Simple linear cost functions (table 1) were created from 30 lithium ion batteries and 17 lead acid batteriesstorage systems with integrated solar inverter[3,4].Figure 3 shows the two functions.Because of the integrated solar inverter, the expense for the inverter, comprised in the costs of the solar system, has to be subtracted from the storage costs.

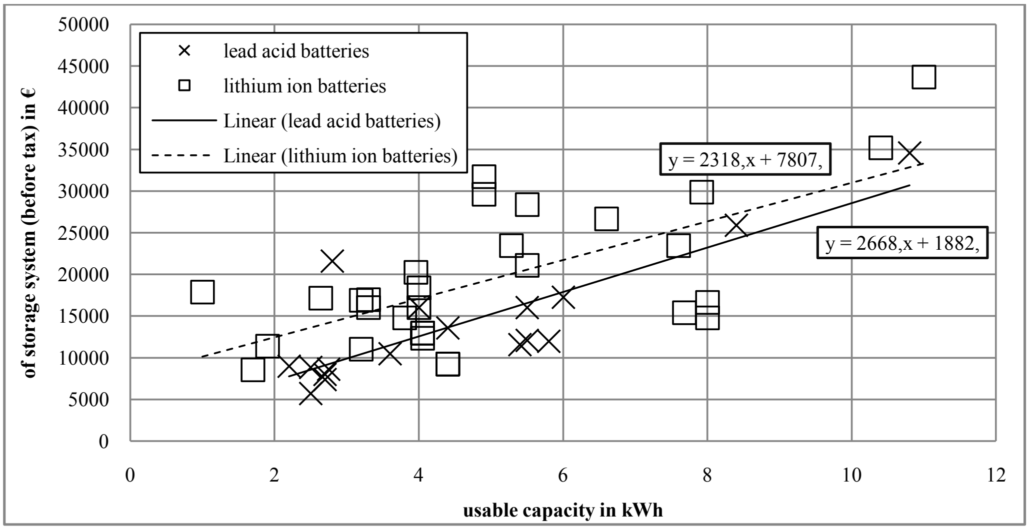

Fig. 3.Possible developments of the electricity tariff.

To determine the costs of redox flow batteries, a cost estimate [5] of Dr. A. Jossen and Dr. L. Jörissen was consulted. They predict costs of 1157 € per kW and 115 € per kWh. Additionally, an amount of 1000 € as margin for the producer,is supposed. The costsof an inverter are also taken into account. Due to this, a redox flow system has the cost equation shown in table 1.

Table 1.Battery technologies.

	Lithium ion battery	Lead acid battery	Redox flow battery
Average asset costs(before tax)	2318.2 €/kWh + 7807.1 €	2668.4 €/kWh + 1882.1 €	115 €/kWh + 1340 €/kW + 1678 €
Life expectancy	18 years	8 years	27 years
Efficiency factor	90 %	80 %	65 %

Capacity loss	20 %	40 %	0 %
Renewal costs (before tax)		204 €/kWh + 173 €	
Average charge / discharge power	1.55 kW/kWh	1.38 kW/kWh	1.46 kW/kWh

The life expectancy of Lithium ion batteriesis lower than the reference period. So the assumption was made, that the system lasts for 20 years. But consequently, the capacity loss rises to 22% in this case. If a lead acid battery system is used,renewal costs for the replacement of the batteries occur every eight years.Regardless of the technology, an installation expense of 1000 € is estimated for the mounting of the storage.

3. Results

To exemplify the result, a photovoltaic system with 6 kWp, south-west orientation and 45° slope of roof, stationed in southern Germany, is analyzed. Annually, the arrangement generates 974 kWh per installed kWp. The factor in the weather equation was adjusted in a way that the period length matches the length of the month. Furthermore, the assumption that no borrowed capital is needed was made. Consequently, the results, presented in figure 4, were generated for the different battery technologies.

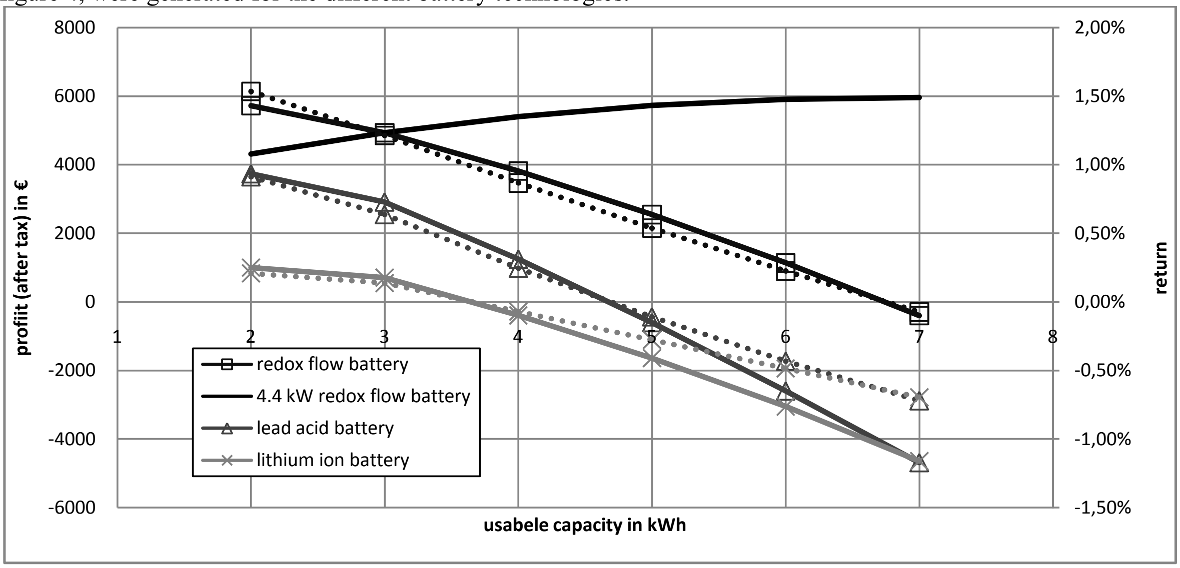

Fig. 4.cost-effectiveness of a photovoltaic application combined with a battery storage (continuous: profit, dotted: return).

Small lithium ion storages are in the black. But clearly, lead acid batteries are more lucrative. This is a result ofthe lower asset costs and despite their bad efficiency factor, low life expectancy and higher capacitance loss. In the range of small capacities, lead acid batteries produce profit. But they generate just a small return of less than 1 % per year. Storage systems with redox flow technology score the highest. However, there is just one European producer supplying batteries bigger than 100 kWh. So these numbers are just theoretical. One advantage of the redox flow batteriesis that the capacity can be changed independently from the power. Thanks to the low costs of 115 € per added kilowatt-hour capacity, the profit raises with higher battery sizes in the considered range if the power is fixed at 4.4 kW. This is thanks to the low costs of 115 € per added kilowatt-hour capacity.Unlike that, the profitability of lithium ion and lead acid batteries declines with bigger sizes because of the high costs of every additional kilowatt-hour (see table 1).

3.1. Variation of electricity price prediction

Instead of Mr. Oettinger's prediction, a percentage increase of annually 5 % is now used to simulate the future increase of the electricity tariff. In figure 5 you can see how the result changes.

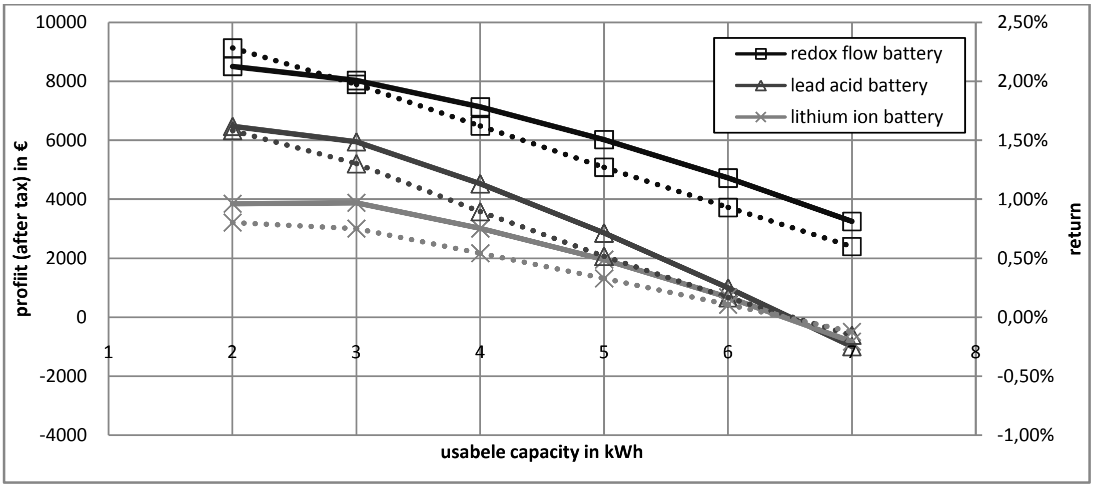

Fig. 5.cost-effectiveness with percentage increase of electricity tariff (continuous: profit, dotted: return).

In this scenario, the arrangement with lead acid batteries reaches a return of 1.58 % (profit: 6480 €). Compared to that, a photovoltaic system without a storage achieves a return of 3.83 % (profit: 11136 €) and if electricity tariffs stabilize, still 3.10 % (profit: 9025 €). But in this case, only 48 % of the electric power consumption is self-produced and just 29 % of the produced electricity is self-consumed. Using a 2 kWh lead acid storage, those numbers raise to 63 % self-sufficiency and 47 % self-consumption. By increasing the capacity to 4 kWh, 75 % self-sufficiency and 51 % self-consumption can be achieved. But in this case, the profit drops to 4527 € (return: 0.90 %) and 1247 € (return: 0.25 %) for stabilizing electricity tariffs.

3.2. Calculationof an actualstorage

If we do not consider a general, average storage system but a real system with a good price capacity ratio, the calculation shows a better financial outcome. For example, if you operate a lead acid battery system with a capacity of 2,5 kWh for 4650 € (after tax), you could make a profit of 5901 € – 8802 € (return: 1.52 % – 2.27 %), depending on the electricity tariff development.

3.3. Variation of user behavior

The user behavior also has a huge influence on the cost-effectiveness. To illustrate this, the start of cooking and the use of the dishwasher afterwards, were changed on workdays from 17:30 to 13:00 and 19:30. Table 2 shows the results for a photovoltaic system with a 4 kWh lead acid battery with stabilizing electricity prices.

Table 2.Profitability by different user behavior (increase of electricity price by five percent).

Start of cooking	Profit (after tax)	Return
13:00	6.632 €	1.31 %
17:30	4.527 €	0.90 %
19:00	3.420 €	0.68 %

Like table 2 clarifies, even if you have a storage system, you should manage to get high consumptions in times of much sunshine.

3.4. Government grant

To increase the profitability and therefore the use of storage systems, the German government started a support program in May 2013. People can get up to 600 € per kilo watt peak installed.But if the promotion is used, the feed-in is limited to 60 % of the nominal power. With these public aids, the return ofan installation with a 2 kWh lead acid battery raises to 1.44 % – 2.11 %, depending on the electricity prices′ development. The return of a 4 kWh lead acid battery system reaches 0.96 % – 1.60 %.

3.5. Variation of weather calculation

The following table shows the results for different rates of change in weather. The period length that is used to simulate the change in the solar irradiance is set from one month to half a month and a quarter month.

Table 3. Variation of weather formula (4 kWh lead acid storage system and a increase of electricity price by five percent).

Period length	Profit (after tax)	Return
One month	4.527 €	0.90 %
Half month	4.520 €	0.89 %
Quarter month	4.510 €	0.89 %

Table 3 shows that thespeed ofchange in the weather has just a low impact on the outcome of the calculation.

4. Conclusions and Discussion

The high interest in storage systems is not surprising considering the current, ubiquitous debate about risen electricity fees. Due to the high asset costs of storage systems, the cost effectiveness of a solar system is clearly reduced and one is risking a negative return if the application is not configured properly. Therefore, an individual technical and economical optimization is highly recommended, especially concerning the storage size. Redox flow batteries have a high financial potential and outrank the other two studied battery technologies. But itremains to be seenwhether redox flow systems will be available for this application and whether the cost prediction is applicable.Despite poor efficiency, low operating life and high capacity loss,lead acid batteries systemsare surprisingly more profitable than lithium ion systems.

Also the market incentive program for storages of the German government improves the financial results clearly. But even with this support, the return of an installation without storage is about twice as large.

Generally, different parts of the house are connected to different electrical phases. That means if a small storage system, that doesn’t support three-phase feed-in, is used, the parts of the house connected to different phases are not supplied. So this has to be considered when planning or reckoning a real system.

In the future, these systems will become more and more interesting just because the investments seem to keep on declining and the electricity prices will keep on rising. Furthermore, it will be interesting if battery prices drop and if lithium ion batteries will be the right choice and assert themselves.

Acknowledgements

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